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METHANE EMISSION FROM RICE CULTIVATION: GEOGRAPHIC AND SEASONAL DISTRIBUTION OF CULTIVATED AREAS AND EMISSIONS

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Abstract. We present high-resolution global data bases on the geographic and seasonal distribution of rice cultivation and associated methane emission. The data bases were developed by integrating extensive and eclectic information on the cultivation of rice in all 103 rice-producing countries of the world. The geographic distribution of rice-growing locations was developed by combining a 1° resolution land-use data base identifying rice-farming regimes, a 1° resolution data base of countries of the world, and country statistics on areas of annual rice harvest available from the U. N. Food and Agriculture Organization. The seasonal distribution of cultivated rice areas was derived via the integration of the data base on rice-growing locations with information on cultivation activities and rice cropping practices for each rice-producing country of the world; this information included seasonal rice-cropping calendars for individual countries and statistics or estimates of the seasonal distribution of annual harvest areas in each crop cycle. Since the causes of the variability in methane fluxes from flooded rice fields have yet to be quantified, we did not attempt a new estimate of the role of rice cultivation in the global emission of methane. We evaluate, instead, the temporal and spatial distribution of emissions from a hypothetical annual source of 100 Tg methane. In 1984, 1475 x $10^9 m^2$ of rice was harvested in 103 countries. Although rice cultivation extends from about 50°N to 50°S, 48% of the harvest area is confined to a narrow subtropical zone from 30°N to 20°N, while another 35% is harvested in the 10° zones directly to the north and south. Globally, about 60% of the harvested rice area is managed under a triple rice crop system, ~15% is double cropped, and 25% is harvested from fields planted for rice once a year. In China and India, which together account for 52% of the world's harvest area, rice is harvested predominantly under a triple-crop system. These patterns suggest that much of the potential for multiple rice cropping is currently exploited. In this analysis, methane emission is proportional to the area and duration of each harvest so that the seasonal, zonal and country patterns of annual methane emission mimic the distribution of rice-harvest areas. Although rice is grown throughout the year, the close coupling of rice cultivation with climate results in the concentration of about 55% of the annual methane emission into four months from July through October and almost half the total emission in latitudes between 30°N and 20°N.

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1. INTRODUCTION

Methane is a radiatively and chemically reactive trace gas in the atmosphere. Its abundance in 1984 was 1627 ppbv, about double that in the pre-industrial era, and is increasing at the rate of ~1% per year [Steele et al., 1987]. The methane increases since 1850 have contributed a cumulative radiative forcing of the atmosphere that is ~35% that caused by the increases in carbon dioxide over the same period [Hansen et al., 1988].

Rice is a staple food crop for over half of the world's population. About 90% of the global rice area is harvested from flooded fields whose anaerobic conditions are prime sites for methane production. This source of methane is generally believed to contribute 10–30% of the global methane source [Ehhalt, 1974; Cicerone and Oremland, 1988; Wahlen et al., 1989] and, because of its close association with human populations, to play a major role in the trend of increasing atmospheric concentrations. Rice is grown in a multitude of environments ranging from the humid tropics to temperate regions of the USSR. Even in tropical and subtropical Asia, where over 90% of the rice area is harvested, myriad biotic and abiotic factors such as phenology, temperature, and water status naturally affect rates of methane production and emission. Recent measurements suggest that the type of fertilizers applied and the timing and mode of the application may also be important factors. At the present time, these local agricultural, economic and cultural factors are impossible to document over large areas and therefore introduce unquantifiable measures of uncertainty into estimates of the global emission of methane from the cultivation of rice.

In this study, we focus on the global and seasonal distribution of rice cultivation. The monthly distribution of rice cultivation areas are presented at 1° resolution for the globe. Because the causes of the variability in methane fluxes from flooded rice fields have yet to be quantified, an attempt to arrive at a global annual emission may be unrealistic at this time. We present, instead, a sensitivity analysis that emphasizes patterns in the temporal and spatial distribution of emissions based on an annual hypothetical source of 100 Tg (10^{12} g) methane.

This paper is the third in a series on the distributions of the major methane sources. The first two papers are on methane emission from natural wetlands [Matthews and Fung, 1987] and from domestic animals [Lerner et al., 1988]. As in the earlier papers, an attempt is made to document, with all available information, the spatial and temporal distributions of the sources. These distributions can then be used in two- and three-dimensional atmospheric transport models to test hypotheses about the global budget of methane (I. Fung et al., Three-dimensional model synthesis of the global methane cycle, submitted to *Journal of Geophysical Research*, 1990, hereinafter referred to as Fung et al., 1990).

A magnetic tape of the global data bases will be available from the National Center for Atmospheric Research (Boulder, Colorado) and the NASA Climate Data Center (Goddard Space Flight Center, Greenbelt, Maryland).

2. DATA AND METHODOLOGY

The spatial and seasonal distribution of rice cultivation and associated methane emission was derived using several complementary types of information. The main types were rice-growing locations from a global land-use data base, total areas of annual rice harvest from the U. N. Food and Agriculture Organization (FAO) country statistics, seasonal rice cropping calendars for individual countries, and estimates of the seasonal distribution of annual harvest areas in each crop cycle. For several countries that are either extensive in area or are significant rice producers, regional data were incorporated. Sources of data used are listed in the appendix by region.

The FAO figures reflect annually harvested rice area, in contrast to cultivation area which is the area of land on which rice is grown. Therefore, in the FAO statistics, land cropped for rice multiple times in one year is counted multiple times. Harvest areas are larger than cultivation areas in countries where rice is grown and harvested more than once on the same land parcel in a single year; these areas are equal in countries where a single rice crop is harvested from the fields.

The following sections describe the development of the data into individual components of the final data base: locations of rice cultivation, harvested rice areas by country, and seasonal distribution of actively growing rice fields. Finally, seasonal and geographic patterns of methane emission resulting from a prescribed 100 Tg annual source are presented.

2.1. *Rice-Cultivation Locations*

The 1° digital land-use data base of Matthews [1983], with 119 land-use types, was the primary and initial reference for determining rice-growing locations on a global scale. Eighteen land-use types, primarily dominated by rice, were selected from the data base. Examples of these systems include intensive subsistence irrigated rice, extensive subsistence farming with rice dominant, and large- and small-scale commercial farming with rice dominant. A few of the selected farming systems are more general (e.g., small-scale commercial farming with irrigated grain dominant) and were included in order to capture rice-growing regions that would not otherwise have been included, for example, in India.

The quality and detail of land-use information available to compile the global data set of Matthews [1983] varied among countries. While it is difficult to evaluate possible errors in data sets of this type, it is probable that there is greater uncertainty associated with omissions (or generalizations) of agricultural information than with incorrect data per se. In other words, we are reasonably certain that rice is grown in those locations for which there is specific information about the cultivation of rice. However, we are not sure that rice is absent from other areas which lack information about crop combinations.

We used the land-use data base solely to determine locations of rice farming and not for determining areas for the following reasons. First, reliable and recent statistics on rice-harvest areas are available from FAO and other sources (see next section). In the case of FAO, statistics are available annually, which allows for updates. Second, this level of general use is compatible with the topical quality of the land-use data base which was designed to reflect the distribution of agricultural systems on a global scale. For this application, it was sufficient only that the 1° cells selected for each country occupied an area at least equal to the country's reported total harvested rice area. This threshold test for rice-producing countries simply assured that the location data base could accommodate the most extreme case in which all the harvested rice is grown during a single annual crop cycle.

Additional, alternative information on locations of rice farming in China and Brazil was compiled and incorporated into the data base because the appropriate information was available and we were aware that the Matthews [1983] land-use data for Brazil were incomplete.

Data on rice-farming locations in China were compiled in digital form at 1° resolution from a 1:4M scale map of vegetation and land-use covering the entire country [Hou, 1979]. The map identifies seven systems of rice cropping, such as summer rice and winter wheat (two crops per year), double rice and winter wheat (three crops per year), and triple rice with subtropical crops (three crops per year). We digitized the information at 1° resolution, recording latitude, longitude, dominant and subdominant cover types, and percentage of the cell covered by types. This data set was overlaid on the land-use data base to identify rice-cultivation locations in each province of the country. Since the two sources, which were derived entirely independently, gave very similar distributions, we were confident that the patterns were generally reliable.

Brazil, with a harvested rice area equal to about 4% of the global total, is the only country outside Asia with a significant area of rice cultivation. However, because land-use information for Brazil from the Matthews data set was scanty, no rice locations were identified via the land-use data base. Rice-growing areas were located using a land-use map of the state of Rio Grande Do Sul, which the *World Atlas of Agriculture* [Committee for the World Atlas of Agriculture, 1969-1976] indicates as the primary region of rice cultivation. Latitude, longitude, and percentage of the cell in rice cultivation were recorded from this map. Information was recorded at 0.5° resolution and recompiled at 1° resolution, so that thirteen 1° cells were added in Brazil. Since we knew there was some rice cultivation occurring in northern areas, we allowed a few commercial land uses (e.g., plantations and small-scale commercial farming) as rice locations, which increased the Brazilian locations by another thirteen 1° cells.

This initial distribution of selected land uses provided sufficient locations for most of the major rice-producing countries (e.g., over 90% of the global harvest area was accounted for in this procedure). However, for more than half of the 103 rice-producing countries listed by FAO, the land-use data base identified either no rice-cultivation cells or an insufficient number of cells to accommodate the FAO area. Despite the large number of countries involved (61), the total area amounted to only about 7% of the global total. Several methods were used to identify rice-cultivation locations in these countries.

In the case of small countries comprising a few 1° cells, e.g., Belize and Bhutan, the FAO rice area was distributed throughout all cells in the country. For larger countries, one of two methods was used. If the area of harvested rice was close to the area of agricultural cells in the country, all agricultural cells were allowed as rice locations. (In this case, agricultural cells include all land locations except those designated in the land-use data base as ice, no use, lumbering, or rough grazing [see Matthews, 1983; Lerner et al., 1988]). This method was applied primarily in Central and South America and in Africa and accounted for about 3% of the world's total rice-harvest area. For countries with extensive agricultural areas where this method was inappropriate, a limited number of alternative land-use types were assumed to be associated with rice and were allowed as locations for rice cultivation. Examples of these farming types are extensive subsistence farming dominated by grain or by mixed tropical crops, small-scale commercial farming dominated by grain, and plantations. The combination of these selected land uses varied among countries, but all were chosen because their areas were reasonable approximations of FAO rice areas and they were land-use types that could likely be associated with rice. This method was used in a few European countries, several subdivisions of India, China, and the United States, and in Central and South America. The final data set of rice-cultivation locations includes 949 1° cells.

2.2. *Rice-Harvest Areas*

The data base discussed above provided potential ground area on which rice cultivation could occur. The next step was to merge annual harvested rice areas, by country, with the location data base. Statistics on areas of harvested rice for all rice-growing countries of the world are available from the annual production yearbooks published by FAO. We used 1984 areas from the *1984 FAO Production Yearbook* [*FAO*, 1985], which included 103 countries; the figures can be easily updated to other years. These FAO reports provide the areal sum of harvest activity during a year but identify neither the relative contributions of multiple- and single-cropped areas to the total, nor the area actively growing at various times throughout the year.

FAO was the sole and consistent source for country totals of harvested rice areas. For several large countries, rice areas for each political subdivision within country boundaries was needed to reduce uncertainties in the distributions. This supplemental information was available for China and India, the two largest producers, as well as for the United States and Australia. Regional statistics on the distribution of rice areas for 28 provinces of China and 25 states of India were compiled from the U. S. Department of Agriculture's (USDA) *Agricultural Statistics of the People's Republic of China, 1949–1982* [1984] and the 1984 *Indian Agricultural Atlas*, respectively (see appendix). The Indian statistics were for 1982-83, so the country total from this source was normalized to the 1984 FAO value, and the regional distributions were then recomputed. Rice areas, by state, for the United States were compiled from the USDA's *Agricultural Statistics 1984* [1984] (see appendix).

A 1° digital data base of countries of the world was used to identify cells for each country. A full discussion of the country data base is given by Lerner et al. [1988]. In brief, the data base consists of 187 countries; seven large countries are further subdivided into smaller political entities. The subdivided countries are Australia, Brazil, Canada, China, India, the United States, and the Soviet Union. Each 1° cell has an integer code identifying the country or subdivision. Codes are organized so that subdivisions can be implemented or ignored. A single code identifies all water cells; Antarctica is treated as one entity.

The annual rice-harvest areas were located into appropriate political units using the country data base (including the subdivisions for China, India, the United States and Australia) and distributed into rice-cultivation locations within political units using the data base discussed in section 2.1. The total rice-harvest area for each country or subdivision was distributed uniformly among all 1° rice cells in each political unit. Since the FAO rice areas were almost always smaller than the total area of 1° rice cells in a country, this procedure resulted in a data base of areal percentages of 1° cells potentially cultivated with rice at some time during the year. Plate 1 shows the resulting global distribution of annual rice-harvest areas. The unit is percentage of 1° cells and the variations among countries reflect the cumulative intensity of rice-harvest over the entire year.

According to FAO [1985], the global area for rice was 1475 x $10^9 m^2$ in 1984, more than 90% of which was in Asia. Table 1a shows 1984 FAO rice-harvest areas for all rice-growing countries; areas for regions within India and China are shown in Tables 1b and 1c, respectively. In both India and China, which together account for 52% of the world's rice area, cultivation of rice is ubiquitous but strongly concentrated in a few regions. Brazil accounted for ~4% of the world's harvested rice area, similar to that of Vietnam and Burma. Brazil's area is more than twice the area of Japan or Pakistan, and about four times that of Cambodia, Nepal, North Korea, Malagasy, or the United States. Indonesia, Bangladesh, and Thailand annually harvest areas in the range of 100 x $10^9 m^2$, each about 7% of the world's total. Minimal contributions to the global area, totaling ~10%, come from a large number of countries scattered throughout Africa, Europe, and the Americas (Plate 1, Table 1).

2.3. *Seasonality of Crops (Crop Calendars)*

As was mentioned above, FAO production yearbooks provide information on the total area harvested for rice during the course of a year but indicate neither the number and duration of crops grown throughout the year nor the area devoted to individual crops during the year. We compiled information on the seasonality of rice crops from a series of crop calendars which give planting and harvest dates for individual agricultural products, by country. The most complete were FAO's *Crop Calendars*, and *Foodcrops and Shortages* as well as the International Rice Research Institute's *World Rice Statistics 1985* (see appendix).

Crop calendars give the dates of planting and harvest for up to three rice crops per year, depending on the country. In the FAO *Crop Calendars*, dates are given in months and decades (10-day periods in a month). Since there is some year-to-year and regional variation in these dates, "early", "bulk" and "late" dates are given for planting and harvest of each crop. We used the bulk dates of planting and harvest since they are the most representative of individual countries' agricultural regimes.

Relatively precise, multiple-crop calendars were available for most rice-growing countries from the sources mentioned above. For the provinces and states of China and India, calendars for each of three annual rice crops were available from the same sources consulted for rice-harvest areas. Additional, often anecdotal, information about rice-cropping practices was compiled from various atlases and from volumes in the Foreign Area Studies series, which includes, for example, *Area Handbook For Pakistan* and *Burma — A Country Study* (see appendix). Such information consists of, for example, commentary about relative distributions of harvested areas in the year. When possible, crop calendars derived from these sources for individual countries were compared with site specific information [e.g., Malingreau, 1986; Rao and Rao, 1987]. Also consulted was Huke's [1982] report of 1970s areas of rice cultivation by water regime in Asian countries which includes general indications of seasonality by referring to wet and dry seasons.

Table 1 presents the final compilation of crop calendars for all 1984 rice producers listed by FAO. Table 1a gives, for rice-growing countries other than India and China, calendars denoting planting and harvest months for each rice crop grown during a year. Dropped dashes indicate that no rice is growing during the month; months in which rice is either planted or harvested and therefore growing for only part of the month are designated with "1"s; if rice is

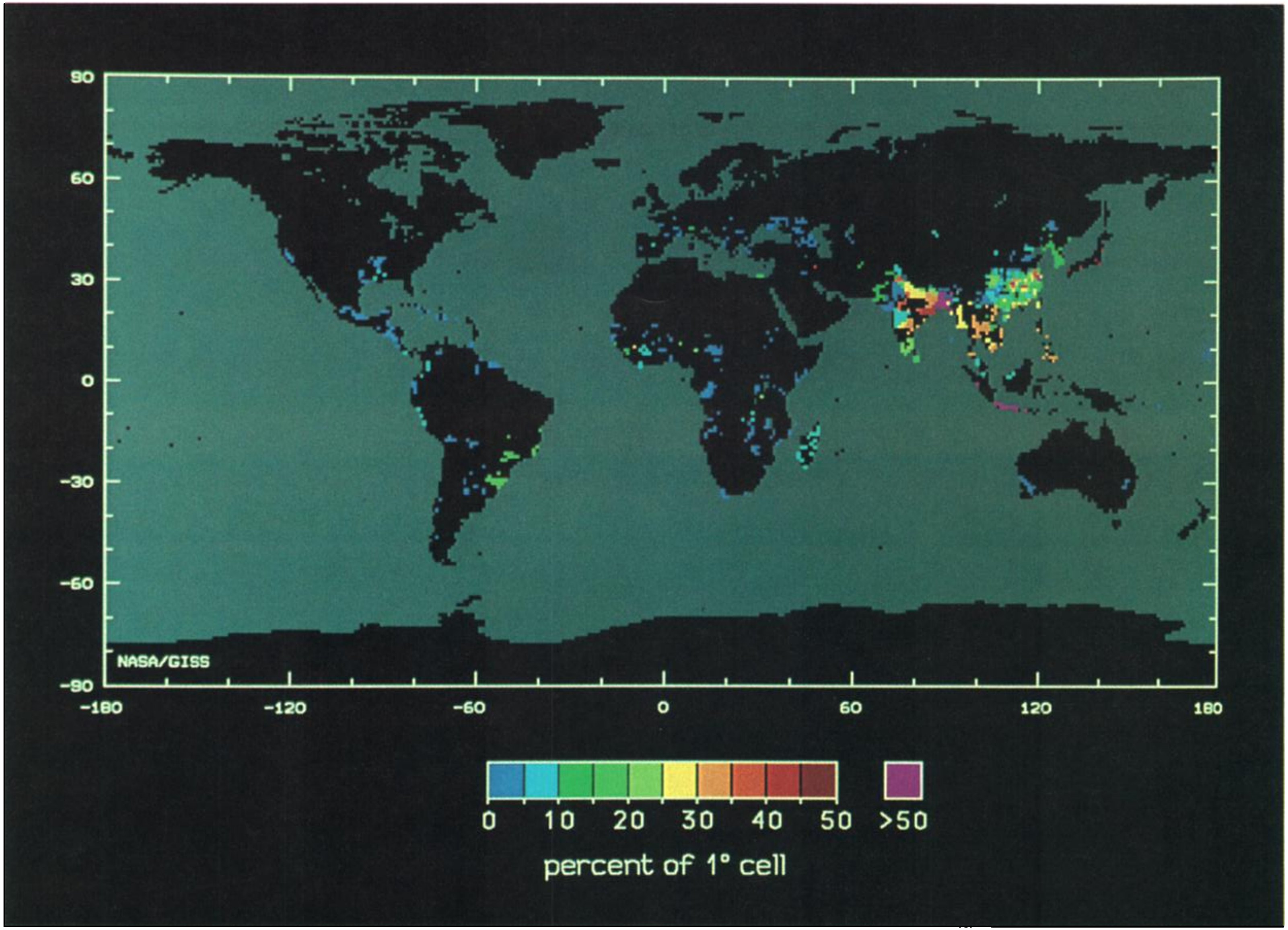

Plate 1. Geographic distribution of annual rice-harvest areas. The unit is percentage of 1° cells, and the variations among countries reflect the cumulative intensity of rice harvest over the entire year.

TABLE 1a. 1984 Harvested Rice Areas, Percentage of Total Area Planted in Seasonal Crops (C1, C2, C3), and Seasonal Crop Calendars for All Rice-Producing Countries of the World

Country	Total Area, $10^9 m^2$	C1 % Area	C1 Calendar JFMAMJJASOND	C2 % Area	C2 Calendar JFMAMJJASOND	C3 % Area	C3 Calendar JFMAMJJASOND
India [a]	428.00						
China [b]	336.86						
Bangladesh	105.00	30	___12221____	60	______122221	10	1221________
Thailand	97.00	90	______122221	10	__12221_____		
Indonesia [c]	97.00						
Vietnam	56.20	60	_____1222221	40	_1221_______		
Brazil	53.56	100	221_______12				
Burma	46.80	100	_____1222221				
Philippines	33.30	65	_____12221__	35	1221________		
Japan	23.15	100	____122221__				
Pakistan	19.99	100	______12221_				
Cambodia	13.90	90	_____1222221	10	221________1		
Nepal	13.35	80	_____1221___	20	______12221_		
Korea, Republic of	12.31	100	_____12221__				
Malagasy	12.00	100	22221____122				
U.S.A.	11.26	100	____122221__				
Korea, D.P.R.	8.30	100	____12221___				
Sri Lanka	7.50	65	221______122	35	___12221____		
USSR	6.88	100	____12221___				
Malaysia	6.60	55	1________122	30	____12221___	15	1_____122222
Taiwan	6.60	60	_____1222221	40	_1221_______		
Laos	6.10	100	______122221				
Nigeria	6.00	100	____12221___				
Egypt	4.20	100	____122221__				
Iran	4.20	100	____12221___				
Guinea	4.00	100	____122221__				
Ivory Coast	4.00	100	__122221____				
Sierra Leone	4.00	100	____1222221_				
Colombia	3.64	75	__1222221___	25	________1221		
Zaire	3.25	100	_12221______				
Tanzania	2.70	100	22221_____12				
Peru	2.40	100	22221____122				
Afghanistan	2.12	100	_____12221__				
Liberia	2.10	100	______122221				
Mexico	2.04	100	____1222221_				
Italy	1.78	100	____12221___				
Cuba	1.51	100	____1222221_				

TABLE 1a. (continued)

Country	Total Area, 10^9 m^2	C1 % Area	C1 Calendar JFMAMJJASOND	C2 % Area	C2 Calendar JFMAMJJASOND	C3 % Area	C3 Calendar JFMAMJJASOND
Venezuela	1.51	100	_____12221__				
Ecuador	1.50	100	12221_______				
Guinea Bissau	1.45	100	____122221__				
Mali	1.30	100	______122221				
Bolivia	1.21	100	221_______12				
Argentina	1.18	100	2221______12				
Dominican Republic	1.15	100	_____12221__				
Australia	1.13	50	2221_____122	50	2221______12		
Panama	0.96	100	____12221___				
Guyana	0.93	100	____122221__				
Uruguay	0.79	100	21_____12222				
Spain	0.73	100	____12221___				
Costa Rica	0.70	100	_____12221__				
Mozambique	0.70	100	122221______				
Surinam	0.70	100	____122221__				
Senegal	0.66	100	______12221_				
Turkey	0.64	100	____122221__				
Haiti	0.58	100	____122221__				
Ghana	0.57	100	_____1222221				
Chad	0.51	100	_____122221-				
Iraq	0.48	100	____122221__				
Nicaragua	0.45	100	_____122221_				
Malawi	0.42	100	222221_____1				
Chile	0.40	100	2221______12				
Paraguay	0.32	100	221_______12				
Bhutan	0.31	100	____12222221				
Romania	0.31	100	____122221__				
Burkina Faso	0.30	100	_____122221_				
Portugal	0.30	100	___122221___				
Cameroon	0.23	100	1_______1222				
Niger	0.23	100	_______12221				
Honduras	0.22	100	____122221__				
Angola	0.20	100	2221______12				
Gambia	0.20	100	______122221				
Guatemala	0.20	100	___1222221__				
Uganda	0.20	100	22221_____12				
Bulgaria	0.16	100	___12221____				
Central African Republic	0.15	100	_____122221_				

TABLE 1a. (continued)

Country	Total Area $10^9 m^2$	C1 % Area	C1 Calendar JFMAMJJASOND	C2 % Area	C2 Calendar JFMAMJJASOND	C3 % Area	C3 Calendar JFMAMJJASOND
El Salvador	0.15	100	_____122221_				
Greece	0.14	100	____12221___				
Comoros	0.13	100	12221_______				
Hungary	0.13	100	____122221__				
Togo	0.13	100	____1222221_				
Fiji	0.09	100	_1221_______				
France	0.09	100	___1222221__				
Kenya	0.09	100	_____1222221				
Yugoslavia	0.09	100	____122221__				
Zambia	0.08	100	22221______1				
Benin	0.06	100	____122221__				
Mauritania	0.05	100	_____122221_				
Trinidad & Tobago	0.05	100	______12221_				
Albania	0.04	100	____122221__				
Congo	0.04	100	2221______12				
Sudan	0.04	100	_____12221__				
USA/Puerto Rico	0.03	100	____122221__				
Belize	0.02	100	____1222221_				
Brunei	0.02	100	1________122				
Burundi	0.02	100	222221____12				
Morocco	0.02	100	_1222221____				
Solomon Islands	0.02	34	12221_______	33	____12221___	33	1_______1222
French Guiana	0.01	100	_12221______				
Jamaica	0.01	100	______122221				
Rwanda	0.01	100	222221____12				
Somalia	0.01	100	1_______1222				
South Africa	0.01	100	222221____12				
Zimbabwe	0.01	100	22221______1				
Global Total	1475.19						

Country totals are from FAO [1985]. Calendar months are indicated by initial letter of month. Calendar symbols: _, no rice growing; 1, planting or harvest month, rice growing for half the month; 2, rice growing for full month.

[a]See Table 1b for seasonal areas and calendars for individual states.

[b]See Table 1c for seasonal areas and calendars for individual provinces.

[c]Rice is grown in all 12 months of the year; the monthly cultivated area was calculated from published monthly values of areas planted and areas harvested. Areas for January through December are: 39.77, 46.56, 40.74, 27.16, 20.37, 19.40, 16.49, 10.67, 2.91, 1.94, 8.73, 24.25.

TABLE 1b. 1984 Harvested Rice Areas, Area Planted in Seasonal Crops and Seasonal Crop Calendars for the States of India

State	Total Area, $10^9 m^2$	Autumn Area	Autumn Calendar JFMAMJJASOND	Winter Area	Winter Calendar JFMAMJJASOND	Summer Area	Summer Calendar JFMAMJJASOND
Uttar Pradesh	56.18	34.82	_____12221__	21.33	______12221_	0.03	12221_______
West Bengal	55.06	7.20	____12221___	43.98	______12221_	3.88	2221_______1
Madhya Pradesh	54.18	54.18	______12221_	-	____________	-	____________
Bihar	50.91	6.57	_____12221__	43.80	_______12221	0.54	12221_______
Orissa	45.05	9.44	_____12221__	34.06	______122221	1.55	122221______
Andhra Pradesh	40.71	2.96	___12221____	27.51	1______12222	10.24	1221________
Assam	26.06	7.09	__12221_____	18.59	_____1222221	0.38	2221_______1
Tamil Nadu	20.43	15.34	______12221_	4.95	221________1	0.14	__1221______
Maharashtra	16.97	16.45	______12221_	0.14	221________1	0.38	__1221______
Punjab	14.94	14.94	_____12221__	-	____________	-	____________
Karnataka	12.97	11.06	_____12221__	0.67	221______122	1.06	12221_______
Kerala	9.04	3.90	____12221___	4.00	1_______1222	1.14	1221________
Haryana	5.54	5.54	_____12221__	-	____________	-	____________
Gujarat	5.39	5.39	______12221_	-	____________	-	____________
Tripura	3.17	1.36	__12221_____	1.39	_____122221_	0.42	2221_______1
Jammu & Kashmir	3.11	-	____________	3.11	____122221__	-	____________
Manipur	1.80	0.44	__12221_____	1.36	_____122221_	-	____________
Rajasthan	1.35	1.35	______12221_	-	____________	-	____________
Nagaland	1.26	0.51	___1221_____	0.75	_____1222221	-	____________
Maghalaya	1.23	0.39	__12221_____	0.82	1_____122222	0.02	2221_______1
Arunachal Pradesh	1.02	1.02	__12221_____	-	____________	-	____________
Himachal Pradesh	1.00	1.00	_____12221__	-	____________	-	____________
Mizoram	0.33	0.10	__12221_____	0.23	_____122221_	-	____________
Sikkim	0.17	0.17	_____1221___	-	____________	-	____________
Andaman Islands	0.14	0.14	_____1222221	-	____________	-	____________
India Total	427.83	201.36		206.69		19.78	

Calendar months are indicated by initial letter of month. Calendar symbols: _, no rice growing; 1, planting or harvest month with rice growing for half the month; 2, rice growing for entire month.

TABLE 1c. 1984 Harvested Rice Areas, Area Planted in Seasonal Crops, and Seasonal Crop Calendars for the Provinces of China

Province	Total Area $10^9 m^2$	ER[a] Area	ER Calendar JFMAMJJASOND	DL[b] Area	DL Calendar JFMAMJJASOND	I/SL[c] Area	I/SL Calendar JFMAMJJASOND
Hunan	44.68	19.46	__11221_____	20.37	_____112221_	4.86	____22221___
Guangdong	41.07	19.45	__12221_____	21.02	_____12222__	0.60	____22221___
Jiangxi	34.02	16.50	__11221_____	14.49	_____112221_	3.04	____22221___
Sichuan	31.63	1.11	__12221_____	0.88	_____12222__	29.63	___1222211__
Guangxi	28.25	12.76	__12221_____	13.42	_____12222__	2.07	____22221___
Jiangsu	26.28	3.75	__11221_____	4.02	_____112221_	18.51	____22221___
Hubei	26.20	7.69	__11221_____	8.16	_____112221_	10.35	____22221___
Zhejiang	25.29	11.02	__11221_____	11.78	_____112221_	2.50	____22221___
Anhui	21.52	7.29	__11221_____	5.65	_____112221_	8.58	____22221___
Fujian	16.70	7.15	__12221_____	6.91	_____12222__	2.64	____22221___
Yunnan	10.91	0.46	__12221_____	0.26	_____12222__	10.19	___1222211__
Guizhou	7.79	0.02	__12221_____	0.01	_____12222__	7.76	___1222211__
Liaoning	4.02	-	____________	-	____________	4.02	___122221___
Henan	4.00	-	____________	-	____________	4.00	____12222___
Shanghai	2.76	1.02	__11221_____	1.36	_____112221_	0.38	____22221___
Jilin	2.57	-	____________	-	____________	2.57	___122221___
Heilongjiang	2.27	-	____________	-	____________	2.27	___122221___
Shaanxi	1.63	-	____________	-	____________	1.63	____12222___
Shandong	1.41	-	____________	-	____________	1.41	____12222___
Hebei	1.34	-	____________	-	____________	1.34	____12222___
Xinjiang	0.90	-	____________	-	____________	0.90	____12222___
Ningxia	0.50	-	____________	-	____________	0.50	___122221___
Beijing	0.50	-	____________	-	____________	0.50	____12222___
Tianjin	0.34	-	____________	-	____________	0.34	____12222___
Nei Monggol[d]	0.16	-	____________	-	____________	0.16	___122221___
Shanxi	0.09	-	____________	-	____________	0.09	____12222___
Gansu	0.04	-	____________	-	____________	0.04	___122221___
Xizang[e]	0.01	-	____________	-	____________	0.01	____12222___
China Total	336.88	107.68		108.33		120.89	

Calendar months are indicated by initial letter of month. Calendar symbols: _, no rice growing; 1, planting or harvest month with rice growing for half the month; 2, rice growing for entire month.

[a]ER, early rice crop.

[b]DL, double late rice crop.

[c]I/SL, intermediate and single late rice crop.

[d]Inner Mongolia.

[e]Tibet.

growing for the entire month, the month is marked "2." The same information and crop calendars are provided for the subdivisions of India and China in Tables 1b and 1c, respectively.

On a global basis, about 60% of the harvested rice area is managed under intensive triple rice crop systems, ~15% is double cropped and 25% is harvested from fields planted to rice once a year.

Of the 103 countries that produced rice in 1984 (Table 1), India and China together accounted for 52% of the total harvested area. The wide spectrum of climatic, cultural and ecological conditions that prevail throughout both these countries contributes to the variety of resident rice-cultivation regimes encompassing from one to three rice crops per annum (Tables 1b and 1c). Rice is triple cropped in about half the states of India and half the provinces of China. Since most of these regions are large producers, these states and provinces account for 94% and 79% of the total area of harvested rice within their respective countries (23% and 22%, respectively, of the global total). The remaining area in both countries, about 7% of the global sum, is harvested almost exclusively from a single rice crop.

Of the remaining 48% of the world's rice-harvest area (Table 1a), 14% is in four countries where rice is triple cropped (Bangladesh, Indonesia, Malaysia, and the Solomon Islands), 16% is in nine countries where rice is harvested twice a year, and 18% is spread throughout 88 countries that grow a single crop of rice annually. This common pattern of single cropping of rice results from a combination of factors, among them climate restraints (e.g., temperature, precipitation), environmental restraints (e.g., nutrient maintenance through crop rotation), or institutional restraints related to water management or other inputs such as fertilizer.

2.4. *Seasonality of Areas*

The seasonal characteristics of cultivation cycles can affect the emission of methane in several ways. First, the length of the growth period varies with crop cycle: for example, in China, the cultivation period is 3–4 months for the early rice crop, and 4–5 months for rice crops grown later in the year (Table 1c). Second, the magnitude of daily methane fluxes may be related to crop cycle: Schütz et al. [1990] and Wang et al. [1990] presented results of field measurements in Hangzhou, China, showing that the daily methane emission from the early rice crop, averaged over the entire season, was 0.19 g CH_4/m^2 while that from the late rice crop grown on the same field was about 0.70 g CH_4/m^2. To estimate the seasonal distribution of methane emission from rice, we integrated information about the number and duration of rice crops (section 2.3) with information on areas devoted to each harvest cycle.

Although the number of rice crops harvested in each country during a year was given by the crop calendars, it is not always possible to determine from the information available whether multiple rice crops are grown sequentially on the same parcel of land or on different fields in the same region. In other words, multiple cropping can be characteristic of a single plot of land or of a geographic region. Ancillary information about local agricultural practices sometimes provides characteristics of regional cropping regimes but such information is not widely available. In the present study, we assumed multiple cropping regimes to be serial plantings on the same fields.

Eighty-eight countries, accounting for 18% of the global harvested rice area, operate under a single rice crop regime (Table 1a). In these countries, 100% of the annual harvest area was distributed uniformly among all rice cells in the country and activated for the single growth period given by the country calendars. For the most part, these single-crop countries are relatively small rice producers in Africa, Europe, and the Americas. Rice areas for as many as three annual crops in the provinces and states of China and India, respectively, were directly available from the sources mentioned in sections above. These areas, in conjunction with their associated crop calendars, determined the extent of actively growing rice fields on a monthly basis for India and China (Tables 1b and 1c).

These direct methods of determining seasonality of rice areas accounted for the major portion of the global rice harvest, i.e., ~70% of the rice-harvest area and 90 of the 103 rice-producing countries listed by FAO.

For the 13 remaining rice-producing countries, which account for about 440 x $10^9 m^2$, one of several methods was used to estimate areas in each crop cycle. Anecdotal information suggesting proportions of the annual harvest area cropped at various times of the year was available for several countries (e.g., Vietnam and Bangladesh, with ~160 x $10^9 m^2$). In general, these commentaries on multiple cropping were corroborated by the published crop calendars. In the few remaining cases, proportions of the total annual area were estimated for seasons using proportions characteristic of surrounding and similar countries. We had confidence in this technique, since we found similar patterns in seasonal planting among countries for which there was information.

Table 1a shows proportions of the harvest totals growing during each crop cycle in the year with crop calendars for each cycle. For instance, in 1984, Thailand harvested a total of 97 x $10^9 m^2$ of rice: 90% was grown in the first crop (C1) which is planted in July and harvested in December, and 10% was in the second crop (C2) which has a cultivation period lasting from March to July. The climatic regulation of rice cultivation via precipitation is evidenced by the major concentration of rice cultivation in the boreal summer. May and June are common planting months and crops are frequently harvested in October and November, which results in a broad cultivation period that peaks in August.

2.5. *Methane Emission From Rice Cultivation*

The first global estimate of methane emission from rice fields was done by Koyama [1963]. Extrapolating laboratory measurements of methane production in incubated paddy soils at various temperatures, he estimated a global emission of 190 Tg methane from wetland rice. Later studies, usually incorporating simple temperature dependences and different rice areas reflecting publication years, gave ranges such as 280 Tg [Ehhalt, 1974; Ehhalt and Schmidt, 1978], 95 Tg [Khalil and Rasmussen, 1983] and 67–166 Tg [Holzapfel-Pschorn and Seiler, 1986]. Except for the Koyama study, these estimates were based on measurements made in temperate research sites in Europe and the United States.

More recent studies, some of which incorporate new flux measurements from field studies in Asia, have estimated annual methane emissions of similar magnitude and range, e.g., 60–140 Tg [Aselmann and Crutzen, 1989]; 50–150 Tg [Schütz et al., 1989]; 69–111 Tg [Schütz et al., 1990], and 25–60 Tg [Neue et al., 1990]. All of these later estimates, except that of Neue et al. [1990], assume similar global areas of harvested rice; the variations are due to differing assumptions about fluxes, length of growing seasons, and temperature effects. The low value suggested by Neue et al. [1990] results from the assumption that only about half of the global rice-harvest area is emitting methane for the full growing cycle because of moisture and edaphic constraints as well as transport limitations due to plant structure.

Field measurements of methane fluxes from rice are relatively scarce. Until very recently, there were no published measurements for rice grown in Asia which accounts for ~90% of the global rice area and where rice-growing practices differ from those of California and western Europe, where initial measurements were made. Recently, several authors have presented results of field studies carried out in Japan, China, and the Philippines [Yagi and Minami, 1990; Schütz et al., 1990; Neue et al., 1990; Wang et al., 1990]. Results are highly variable and conflicting. Among these studies, flux rates vary from 0.005 g CH_4/m^2/day for a Japanese rice field on andosols amended with mineral fertilizer [Yagi and Minami, 1990] to 0.69 g/m^2/day for a late (second) rice crop grown in Hangzhou, China [Schütz et al., 1990; Wang et al., 1990]. Information about the role of factors previously shown or suggested to be modulators of methane fluxes, i.e., soil type, fertilizer, plant phenology, crop cycle, temperature, and moisture status, is increasing but remains conflicting.

Most previous analyses on the role of flooded rice fields in the methane budget have focused on field measurements of methane fluxes and the factors that affect them. Simple, aggregated statistics on rice-harvest areas, on seasonal cultivation of areas, and on mean temperatures of large regions, were used to calculate global methane emission related to rice cultivation.

Recently, Aselmann and Crutzen [1989] integrated local and seasonal information about rice cultivation to estimate the global emission of methane from this source. In the present study, a major effort was spent on determining the geographic and seasonal distribution of areas of rice cultivation. The general geographic pattern of rice areas derived in this study (Plate 1) resembles the distribution derived by Aselmann and Crutzen [1989]. This effort appeared warranted in light of recent field measurements suggesting that crop cycle, plant phenology, temperature, soil conditions, moisture status, and fertilizer use may play a role in regulating the flux of methane from rice fields. More precise information on the spatial and temporal dynamics of rice cultivation provides the framework for integrating information on these additional characteristics, which vary seasonally and geographically, and allows analysis of derived source distributions using a three-dimensional atmospheric transport model [Fung et al., 1990].

In the preceding sections, we presented new data bases on the spatial and seasonal distribution of rice cultivation. The global annual emission of methane from rice cultivation could be estimated as the product of the methane emission rate, cultivated rice area, and growth period, summed over all crop cycles of rice for all countries. However, measured daily methane fluxes range over more than two orders of magnitude, estimates of the total emission of methane over a harvest cycle vary by a factor of 40 among individual sites, and quantitative evaluations of the role of various controls in the fluxes are elusive. Therefore an improved estimate of the role of rice cultivation in the global methane budget, incorporating the suite of factors suggested as controllers, is still beyond our capabilities at present.

In the following section, we discuss the use of the improved information on rice cultivation to focus on two components of the problem: (1) patterns in the temporal and spatial distribution of rice cultivation and methane emission given by the new data bases presented here, and (2) evaluating the magnitude and pattern of fluxes that yield a prescribed source strength. For this analysis, the annual sum of methane emitted from rice was prescribed at 100 Tg, a number convenient for discussion as well as within the range of current estimates. Setting the source strength at 100 Tg, and using (1) a constant daily flux rate for actively growing areas, (2) rice-harvest areas given by FAO, and (3) growing seasons given by crop calendars for individual countries, results in a calculated flux for actively growing rice areas of 0.5 g CH_4/m^2/day.

3. DISTRIBUTION OF RICE CULTIVATION AND METHANE EMISSION

The latitudinal and seasonal distribution of cultivated rice areas (Table 2a) mimics the pattern of methane emission (Table 2b, Plate 2) and reveals the close coupling of rice cultivation and climate. The

TABLE 2a. Latitudinal and Monthly Distribution of Areas Under Rice Cultivation

Latitude	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Sum*
90° - 80°N	-	-	-	-	-	-	-	-	-	-	-	-	-
80° - 70°N	-	-	-	-	-	-	-	-	-	-	-	-	-
70° - 60°N	-	-	-	-	-	-	-	-	-	-	-	-	-
60° - 50°N	-	-	-	-	-	-	-	-	-	-	-	-	-
50° - 40°N	-	-	-	7	13	20	26	19	13	0	-	-	98
40° - 30°N	-	0	13	20	116	173	181	181	147	77	13	-	921
30° - 20°N	13	21	71	120	181	287	445	555	533	484	300	103	3113
20° - 10°N	26	29	39	40	32	73	161	226	233	219	193	110	1381
10° - 0°	13	14	19	13	19	33	52	58	47	39	33	19	359
0° - 10°S	45	50	45	33	26	20	19	13	0	0	13	26	290
10° - 20°S	19	21	19	13	6	0	-	-	-	6	13	19	116
20° - 30°S	45	43	26	7	0	0	-	-	-	0	27	45	193
30° - 40°S	13	14	6	0	0	0	-	0	0	0	7	13	53
40° - 50°S	0	0	0	0	-	-	-	-	-	-	0	0	0
50° - 60°S	-	-	-	-	-	-	-	-	-	-	-	-	-
60° - 70°S	-	-	-	-	-	-	-	-	-	-	-	-	-
70° - 80°S	-	-	-	-	-	-	-	-	-	-	-	-	-
80° - 90°S	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum	174	192	238	253	393	606	884	1052	973	825	599	335	6524

Unit is $10^9 m^2$.

*The total annually harvested rice area is $1475 \times 10^9 m^2$. However, rice locations are actively growing over varying time periods during the year and the annual sum of monthly growing areas is $6524 \times 10^9 m^2$-month. Fractional contributions of zones and/or months can be computed by dividing table values by the annual sum.

TABLE 2b. Latitudinal and Monthly Distribution of Methane Emission From Rice Cultivation

Latitude	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Sum
90° - 80°N	-	-	-	-	-	-	-	-	-	-	-	-	-
80° - 70°N	-	-	-	-	-	-	-	-	-	-	-	-	-
70° - 60°N	-	-	-	-	-	-	-	-	-	-	-	-	-
60° - 50°N	-	-	-	-	-	-	-	-	-	-	-	-	-
50° - 40°N	-	-	-	0.1	0.2	0.3	0.4	0.3	0.2	0.0	-	-	1.5
40° - 30°N	-	0.0	0.2	0.3	1.8	2.6	2.8	2.8	2.2	1.2	0.2	-	14.1
30° - 20°N	0.2	0.3	1.1	1.8	2.8	4.3	6.9	8.6	8.0	7.5	4.5	1.6	47.6
20° - 10°N	0.4	0.4	0.6	0.6	0.5	1.1	2.5	3.5	3.5	3.4	2.9	1.7	21.1
10° - 0°	0.2	0.2	0.3	0.2	0.3	0.5	0.8	0.9	0.7	0.6	0.5	0.3	5.5
0° - 10°S	0.7	0.7	0.7	0.5	0.4	0.3	0.3	0.2	0.0	0.0	0.2	0.4	4.4
10° - 20°S	0.3	0.3	0.3	0.2	0.1	0.0	-	-	-	0.1	0.2	0.3	1.8
20° - 30°S	0.7	0.6	0.4	0.1	0.0	0.0	-	-	-	0.0	0.4	0.7	2.9
30° - 40°S	0.2	0.2	0.1	0.0	0.0	0.0	-	0.0	0.0	0.0	0.1	0.2	0.8
40° - 50°S	0.0	0.0	0.0	0.0	-	-	-	-	-	-	0.0	0.0	0.0
50° - 60°S	-	-	-	-	-	-	-	-	-	-	-	-	-
60° - 70°S	-	-	-	-	-	-	-	-	-	-	-	-	-
70° - 80°S	-	-	-	-	-	-	-	-	-	-	-	-	-
80° - 90°S	-	-	-	-	-	-	-	-	-	-	-	-	-
Sum	2.7	2.7	3.7	3.8	6.1	9.1	13.7	16.3	14.6	12.8	9.0	5.2	99.7

Unit is Tg methane.

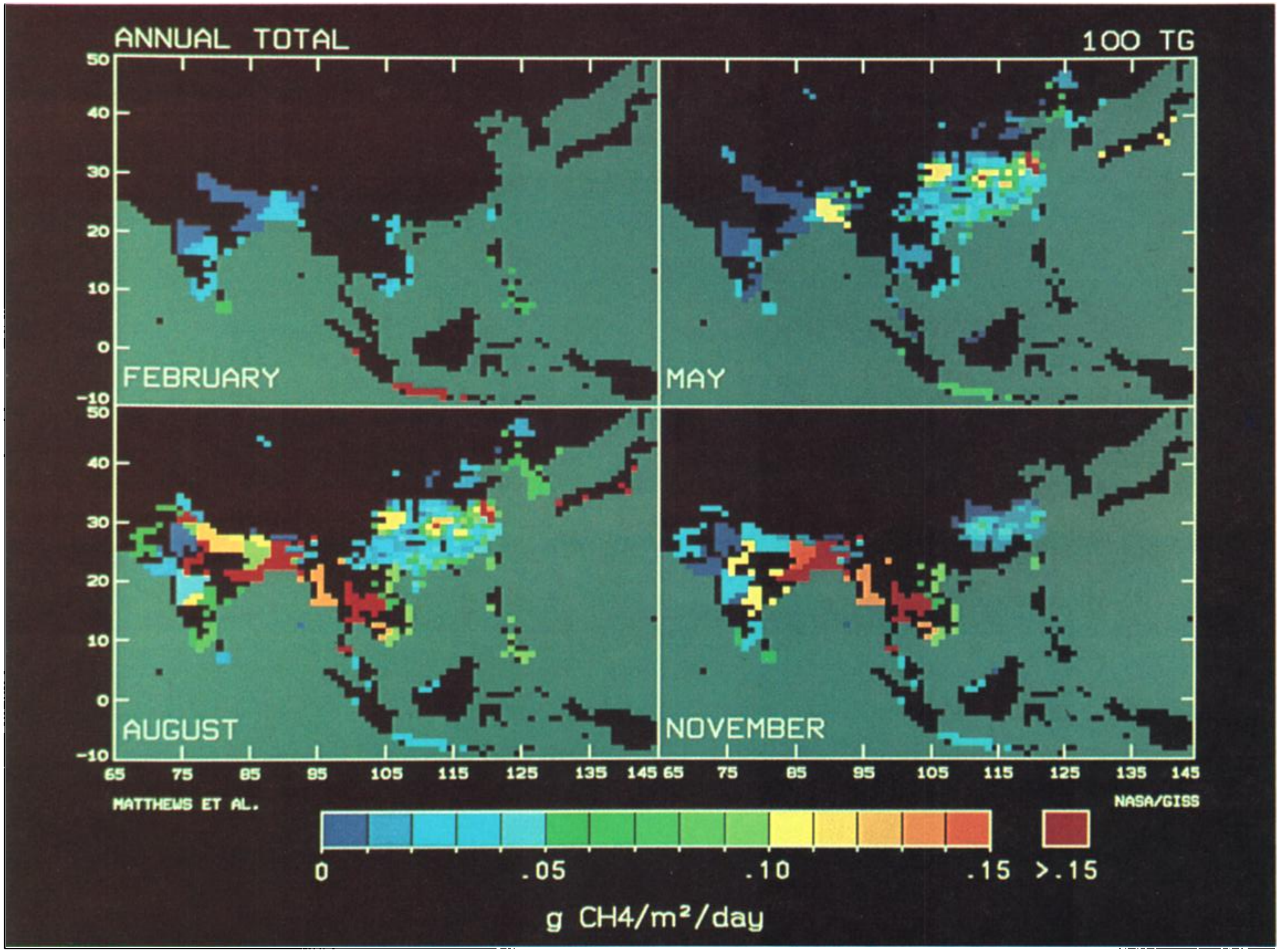

Plate 2. Seasonal distribution of mean daily methane emission rates for the months of February, May, August, and November. The unit is grams CH_4/m^2/day per 1° cell. Values are the product of the daily flux (0.5 g/m^2), month length, and fractional cell area in rice cultivation (Plate 1); therefore the maximum value possible, 0.5 g/m^2/day, would occur in a 1° cell completely cultivated for an entire month.

cultivation of rice extends from ~50°N to ~50°S and occurs primarily under rainfed conditions. Note that while the total rice area harvested in the year is 1475 x $10^9 m^2$, rice locations are actively growing over varying time periods during the year; the annual sum of monthly areas under cultivation is 6524 x $10^9 m^2$-month (Table 2a) reflecting the average growth period of about 4.5 months. With the daily flux rate for this study constant at 0.5 g CH_4/m^2, methane emissions average ~15 g/m^2 per month or ~70 g/m^2 for a complete harvest cycle.

About 48% of the rice-harvest area (3113 x $10^9 m^2$-month / 6524 x $10^9 m^2$-month) falls within the region 30°-20°N, and an additional 21% is from 20°N to 10°N (Table 2a). There is a slight northward shift in the rice belt during the period from January to the boreal summer followed by a southward shift in the fall. Overall, however, these peripheral activities do not play a major role in the global pattern which is controlled primarily by large seasonal variations in the area of cultivation within the northern tropical/subtropical zone regulated by precipitation patterns.

This climatic regulation also produces a temporal concentration of actively growing rice area that peaks in August, although a significant area equal to about 80-90% that of the peak month is in cultivation in July, September, and October (Table 2a). Both June and November are characterized by growing areas of about 600 x $10^9 m^2$; the remaining months have areas <400 x $10^9 m^2$ dropping to lows of about 180 x $10^9 m^2$ in January and February.

This seasonal concentration of rice cultivation results in a similar telescoping of methane emission (Table 2b). About 57% of the annual total is emitted in the four months from July through October. Furthermore, more than 80% of the global source is produced in Asian countries confined to the zone from 40°N to 10°N and almost half the total comes from the narrow zone between 30°N and 20°N.

India harvested 428 x $10^9 m^2$ of rice in 1984 (Table 1b). Only 5% of the total was summer paddy (harvested in summer); the remainder was harvested equally in autumn and in winter. Periods between planting and harvest in India are almost universally four months for the autumn crop, and more characteristically five months for the winter crop and three or four months for the small summer crop. Close to 80% (338 x $10^9 m^2$) of India's total was grown in 12 states where three crops are grown annually. Double cropping of rice is an uncommon practice in India: only four states grow two rice crops, accounting for <2% of the total area for the country. Another nine states harvested the remaining 20% (86 x $10^9 m^2$) of India's area under a single crop regime; about two thirds of this was grown exclusively in the state of Madhya Pradesh. India accounts for 29% of the global rice-harvest area and 28% of the methane emission from rice cultivation.

Patterns among crop calendars of Chinese provinces (Table 1c) are generally less variable than those in India, and crop areas are more evenly distributed among the cropping cycles. For the country as a whole, "early" rice (planted in March-April, harvested in July) and "double late" rice (planted in June, harvested in October-November) each account for ~32% of the annual harvested rice area; the similarity in areas in conjunction with the dovetailing of harvest and planting dates strongly suggests that these crops are grown sequentially on the same fields. (The June-July overlap may reflect the practice of starting rice plants in high density seedling beds and transplanting them after harvest of the early crop.) "Intermediate-single crop late" rice, which includes the northern variety of rice in this study, contributes about 36% of the total and is planted in April-May and harvested in September.

The major rice-producing regions of China, accounting for ~55% of the total rice area, are in the southeastern provinces of Guangxi, Guangdong, Hunan, Jiangxi, Fujian, and Zhejiang. Seasonal harvest patterns here strongly influence the country-wide figures, i.e., major concentration of the rice harvest coming equally from "early" and "double late" crops. Extending to the west and north, the provinces of Sichuan, Jiangsu, and Yunnan, which account for ~20% of the Chinese total, are characterized almost exclusively by "intermediate-single late" rice. Anhui is the only region of significant rice area in which the harvest is equally distributed throughout the three seasons. Overall, 13 of China's 28 provinces grow three rice crops annually and account for 95% of the total harvest area. The remaining 15 regions, with a single crop of "intermediate-single late" rice in a year, are small producers contributing the remaining 5% of the total area. This pattern of a large number of small producers operating under a single rice crop regime mimics the global pattern shown in Table 1a. China accounts for 23% of both global rice-harvest area and global methane emission if daily fluxes are uniform.

Contributions of individual countries to the global emission of methane from rice cultivation closely follow the rice-harvest areas shown in Table 1. Including India and China, Asia accounts for over 90% of the rice-harvest area and methane emission. The remainder comes from small areas of rice cultivation scattered throughout North and South America, Africa, Europe, and Australia (Table 1a, Plate 1).

4. DISCUSSION OF UNCERTAINTIES

Most estimates of the emission of methane from flooded rice fields have been based on simple assumptions about regional rice-harvest areas and cultivation periods; the role of temperature was included in a general way by some workers. Major uncertainties remain regarding the effects of controlling factors such as water status, fertilizer, temperature and phenology. Flux measurements exhibit very large variability and no general quantitative relations have been found to describe the variations in methane fluxes at local scales. Furthermore, information on the distribution of some of these factors is not currently available for most areas. It is possible, however, to evaluate qualitatively the impact of some of the remaining uncertainties.

4.1. *Representativeness of Measurements*

Until very recently, the few published field measurements available for estimates of the global methane emission from rice cultivation were limited to research sites in temperate regions in the United States (California) and Western Europe (Italy and Spain) which may not represent field conditions of Asia where most of the world's rice is grown. The measurement data base is expanding with the addition of field results from Asia [see Bouwman, 1990]. The measurements demonstrate highly variable fluxes and conflicting results regarding the role of regulating factors such as fertilizer and temperature. These fundamental uncertainties translate into uncertainty about the role of rice cultivation in the global methane budget.

The present study approached the problem from a different perspective. Considerable effort was spent on developing high-quality data bases on the spatial and temporal distribution of rice cultivation. This effort directly reduces some uncertainties; the technique also allows integration of complementary data bases on soil characteristics, fertilizer application, temperature or precipitation, when better information about their role in methane emissions is available.

4.2. *Seasonal and Geographic Distribution of Rice Cultivation*

We have general confidence in the reliability of harvested rice areas published by FAO. Furthermore, we do not know of any other globally consistent and more reliable source for such information. While Neue et al. [1990] have suggested that a significant portion of rice-harvest areas may not have conditions appropriate for methane production, we have no information to determine the fraction of the area that produces methane each month for the large number of the rice-growing countries in the world (or even for the major ones). Huke [1982] lists rice-harvest areas by cultivation and water-delivery method with general indications about seasonality for Asian countries (e.g., irrigated, rainfed, or dryland; wet or dry season; shallow, intermediate, or deepwater cultivation). He suggests that about 10% of the global total is grown under dryland cultivation methods. While the various methods of rice cultivation could result in distinctive emission rates, flux data for these various conditions are insufficient at the present time to justify such distinctions. The more important variable, for which information is available, is the length of growth cycles and the seasonal distribution of areas.

In the present study, all areas harvested for rice, as reported by FAO, were assumed to be producing methane at a constant rate throughout their entire growth cycles. Since the total methane emission was prescribed, inclusion of the approximately 10% of the rice area that may be dryland rice has a minimal effect only on the relative distribution of areas on a seasonal basis.

Apparently reliable information on crop calendars and areas of actively growing rice was available for the largest rice growers (i.e., China and India) and were used here. In addition, reasonably good information on the seasonality of areas and crop cycles was available for the majority of important rice-producing countries. This combination suggests that the temporal and spatial distribution of rice cultivation derived here is reasonable. As there is generally only one source of information for each region, quantification of the errors and uncertainties is not possible.

4.3. *Seasonal Flux Variations*

In the present study, we have assumed a constant daily flux for rice areas for their entire growth period. This is a simplification of the intra-seasonal variability shown in the flux measurements [Cicerone et al., 1983; Holzapfel-Pschorn and Seiler, 1986; Schütz et al., 1989; Yagi and Minami, 1990]. Holzapfel-Pschorn and Seiler [1986] ascribed an early maximum flux rate, about five weeks after flooding, to mineralization of organic material already present in the soil; the authors suggest that the largest fluxes, occurring 10–12 weeks after flooding, may be due to the supply of organic matter by root exudates. The measurements reported by Cicerone et al. [1983] show a similar pattern in peak periods, i.e., an early small peak and a larger peak later in the season that continued until field drainage. Including such intracycle variations might further telescope emissions into a short time period (currently, 57% of the global total is emitted in four months), or shift the position of the emission curve in the year.

4.4. *Temperature Effects*

Because of conflicting results about the effect of temperature on methane fluxes, we have not included temperature effects in the present study. In studies of California rice fields, Cicerone and Shetter [1981] and Cicerone et al. [1983] found no clear relationship between methane flux and soil temperature and no significant diurnal variations in methane efflux. Studies of Italian rice paddies, which occur under climatic conditions very similar to those of California, indicated that methane fluxes were strongly dependent on temperature in the upper layer of the soil [Holzapfel-Pschorn and Seiler, 1986]; the authors noted that emission rates approximately doubled, from 13 to 28 mg/m^2/h, as soil temperature increased from 20° to 25°C (Q_{10} = 4). These authors cite Koyama's [1964] lab measurements suggesting an exponential increase in fluxes in these temperature ranges.

Inclusion of a temperature/flux dependence would likely shift the high-emission shoulder periods to earlier months of the year and result in a larger total emission. These effects are demonstrated in the work of Aselmann and Crutzen [1989]. Their 60 Tg annual emission, estimated using a constant daily flux rate of 0.310 g/m^2, increased to ~90 Tg when the temperature effect of Holzapfel-Pschorn and Seiler [1986] was incorporated; in this latter estimate, daily emission rates ranged from 0.3 to 1.0 g/CH_4/m^2 for temperatures between 20° and 30°C. This formulation estimated minimum (January through April) and maximum (August) emissions in the same months as those presented here (Table 2b) but produced higher values for the early months of the major growing season (June and July) balanced by lower emissions for the later months of the season (September through December).

4.5. *Fertilizer Effects*

Cicerone and Shetter [1981] found that the application of fertilizer influenced the relative seasonal distribution of methane emission; i.e., in comparison with the lightly fertilized control plot, the heavily fertilized plot showed larger fluxes early in the season when overall methane activity was low, smaller fluxes later in the season when fluxes in general were elevated, and overall lower methane emission over the growing season. The studies of Yagi and Minami [1990] in Japan showed that applications of mineral fertilizers produced a dramatic but short-lived (~2 week) reduction in methane emissions from rice fields. Furthermore, they found that several plots on the same soils showed a pattern of increasing fluxes when fertilized, respectively, with non-nitrogen, mineral, compost and rice straw amendments. Highest fluxes were measured on peaty soils fertilized with rice straw. In Italy, Schütz et al. [1989] also found significantly elevated efflux of methane with the addition of rice straw, while the application of various mineral fertilizers generally reduced methane emissions by altering amplitudes of seasonal emissions. The suite of fertilizer-induced responses was strongly influenced by the type and amount of fertilizer and the mode of application.

While it appears that various fertilizers affect the production and/or emission of methane from rice fields, the nature of the relationship is not clear. In addition, information on the type and amount of fertilization practiced in rice-producing countries is unavailable at the present time. Therefore the role of fertilizer in the emission of methane from flooded rice fields has not been included in this study.

5. DISCUSSION AND FINAL REMARKS

This work presents data bases on the geographic and seasonal distribution of rice cultivation on a global scale. These data bases were developed by integrating extensive and eclectic information on rice-harvest areas (by country and by region within countries) and rice-cropping practices for all 103 rice-producing countries of the world. These data bases reduce some uncertainties about the temporal and spatial distribution of rice cultivation and its associated methane emission.

Field measurements of methane fluxes from rice paddies show extreme variability that results from the interplay of many factors whose individual roles in the regulation of methane production and emission are poorly understood. For example, in climatically similar environments, the effect of temperature on methane emission may be positive at one site and neutral at another. Similarly, fertilizer amendments have been found to both increase and decrease methane fluxes. Until these relationships can be quantified and information on the regulating factors is available, an improved estimate of the role of rice cultivation in the methane budget is problematic. In the present work, therefore, we concentrated the effort on reducing uncertainties in the spatial and temporal distribution of rice cultivation and used these new data bases to analyze the patterns of methane emission from a postulated global annual emission of 100 Tg CH_4.

Setting the source strength at 100 Tg, and using (1) a constant daily flux rate for actively growing areas, (2) rice-harvest areas given by FAO and (3) length of growing seasons given by calendars for individual countries, resulted in a calculated daily flux for rice-growing areas. In this case, a relatively high daily flux of 0.5 g CH_4/m^2 was required to satisfy the 100 Tg annual emission. While the 100 Tg scenario may not be an extreme assumption [e.g., Cicerone and Oremland, 1988], it should not be considered at this time as more than a potential and convenient benchmark for analysis.

For example, the highest measured mean daily flux of methane from a rice field averaged over an entire crop cycle, 0.69 g/m^2, is that reported by Schütz et al. [1990] and Wang et al. [1990] from a second rice crop in Hangzhou, China. The uniform daily flux of 0.5 g CH_4 required for the 100 Tg source in the present study is higher than most values reported for mid-latitude research sites. Therefore average daily fluxes of methane from rice fields in the tropics and subtropics may be in the upper range of those measured to date and may be much higher than previously anticipated. Alternatively, methane fluxes during the course of cultivation periods may vary even more than indicated by the range of reported measurements, spiking to extremely high values during parts of the season resulting in overall high values for the season.

Finally, the total source strength of methane from rice cultivation may be considerably smaller than the 100 Tg value considered here. The smaller emission is plausible if daily fluxes are lower than suggested here, i.e., are more similar to the majority of reported measurements. An alternative cause for a lower overall contribution from rice cultivation is that flux rates may be higher than those measured in temperate regions but significantly smaller areas may be emitting methane, as was proposed by Neue et al. [1990].

It is unlikely that the role of rice cultivation in the global methane budget will be well constrained in the near future simply by employing extrapolation methods. Successful simulation of the variations of atmospheric methane and its isotopes using a three-dimensional atmospheric transport model provides some cross checks on the sources and sinks derived from direct methods [Fung et al., 1990]. A global methane budget appears to be an under-determined problem, where there are more sources and sinks than there are observations to constrain them. Derivation of a unique methane budget, and the contribution of rice cultivation, requires concerted efforts to measure and understand the factors that promote and limit methane production, consumption, and emission. For rice cultivation, understanding the interplay among climate, substrate, and fertilizer is particularly urgent.

APPENDIX: DATA SOURCES BY REGION

Global or Multicountry

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